FRCM CHAPTER 8
ALARA MANAGEMENT OF ACCELERATOR RADIATION SHIELDING

Revision History

Author	*Description of Change*	*Revision Date*
J. D. Cossairt	1. Changes needed to reflect the transformation of the FESHCom Shielding Assessment Review Subcommittee to the Shielding Assessment Review Panel reporting to the Radiation Safety Subcommittee. 2. Clarifications of details concerning the shielding assessment review process. 3. Remove references to the now obsolete organizational designation of "centers". 4. Minor changes in technical details.	January 2016
J. D. Cossairt	1. Editorial changes made to reflect evolution of the ESH&Q organization at Fermilab	July 2015
J. D. Cossairt	2. Revise Article 811 to incorporate reference to new RP Form 105.	January 2013
J. D. Cossairt	3. Revised to incorporate establishment of the FESHCom Shielding Assessment Review Subcommittee (FSARS). 4. Improve consistency with FESHM Chapter 2010.	August, 2011

	5. Set forth a procedure for obtaining approval for selecting active in lieu of passive shielding cross-referenced to the Director's Exceptions specified in FESHM Chapter 1010. 6. Improve statement of current practices. 7. Rename chapter to better reflect importance of ALARA program. 8. Correct editorial errors.	

CHAPTER 8 ALARA MANAGEMENT OF ACCELERATOR RADIATION SHIELDING

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Radiological control performance is affected by human performance and engineered design features. This Chapter sets forth the policies for the design of new facilities and major modifications to existing facilities. The Appendix to this chapter contains a synopsis and abbreviated bibliography of references on shielding design methodology.

For purposes of this chapter, "dose" means effective dose as defined by International Commission on Radiation Protection (ICRP) Publications 60, 61, 74, and 103. Likewise, the terms "quality factor" Q and "effective quality factor" Q_{eff} are considered to be equivalent to "radiation weighting factor" w_R addressed in ICRP Publications 60, 61, 74, and 103 when comparing older shielding calculations to newer ones.

POLICIES AND PROCEDURES CONCERNING SHIELDING OF ACCELERATORS/BEAMLINES

811 Fermilab Policy on Accelerator Shielding Design

1. Shielding designs shall be well-engineered to maintain occupational and environmental radiation exposures as low as reasonably achievable (ALARA) and compliant with applicable Regulations and U. S. Department of Energy (DOE) Orders.

2. The first choice for initial designs of new facilities or significant modifications of accelerator shielding of existing facilities shall be passive shielding elements designed to achieve areas external to shielding to be classified as minimal occupancy or better in accordance with provisions of Article 236. Reliance on active systems such as radiation safety interlocks and/or beamline instrumentation to achieve radiation safety goals should be chosen only if passive elements cannot, in view of planned accelerator operations, reasonably achieve the level of protection required by the provisions of this Manual.

    a. Should other considerations such as cost, interference with other structures, etc. indicate that non-passive shielding elements are necessary to meet the requirements of Article 236, a request for such an exception shall be prepared with concurrence of the Operating Division/Section Head, the assigned Radiation Safety Officer (RSO), and the Chief Safety Officer.

    b. Such a proposal shall include an approximate comparison of the cost with and without passive shielding including an assessment of the cost of active systems needed (e.g., electronic berms, interlocked detectors, network of loss monitors, etc. and their long-term operational costs.)

    c. The proposal will then be presented as an exception request to the Laboratory Director for consideration in accordance with the provisions of

FESHM Chapter 1010: (http://esh-docdb.fnal.gov/cgi-bin/ShowDocument?docid=332). This request be submitted using R.P. Form 105, "Request for Approval for Interlocked Detectors in Lieu of Passive Shielding".

d. The requirement to apply for a Director's exception in accordance with this section does not apply to the recognized need to, on occasion, apply active systems to existing installations or temporary conditions.

3. The design goal for dose rates in areas of continuous occupancy shall be less than an average of 0.05 mrem/hr and as far below this and as low as is reasonably achievable (ALARA). See Articles 234 and 236 and the Tables associated with those Articles. Dose rates for potential exposure to radiological workers in areas without continuous occupancy shall be ALARA and such that individuals do not receive more than 20% of the applicable limits as stated in Table 2-1.

4. Discharges of radioactive liquid to the environment are covered by provisions of DOE Order 458.1 as implemented under the DOE-Fermi Research Alliance contract. The concentrations should be kept ALARA and in conformance with other chapters of this Manual.

5. Materials and components should be selected to minimize the radiological concerns, both occupational and environmental.

6. Where removable contamination might be associated with accelerator operations, provisions should be made in facility designs for the containment of such material.

7. Internal exposure shall be minimized in accordance with ALARA principles by the inclusion of engineered controls such as ventilation, containment, filtration systems, where practicable and with appropriate administrative procedures (see Article 316).

8. Efficiency of maintenance, decontamination, operations, and decommissioning should be maximized.

9. Criteria for the conduct and review of shielding assessments are set forth in other articles of this chapter.

812 Special Technical Considerations Pertaining to Accelerator Radiation Shielding Design

It is imperative to continue to design accelerator facilities at Fermilab in a way that provides adequate shielding against prompt radiation fields and, to the extent practicable, minimizes

the production of residual radioactivity. Adequate protection of the environment as discussed in other FRCM and FESHM chapters is also required before a given facility is constructed or modified both to assure safe operation and fiscal economy. There are certain technical considerations that apply to accelerator radiation shielding design among which are the following:

1. Radiation weighting factors for various particles that should be used in shielding designs are specified in Table 8-1 unless more detailed energy spectrum information is available.

2. The design of facilities where neutron radiation is anticipated should use a radiation weighting factor of 20 unless measurements or calculations demonstrate that a specific value of radiation weighting factor is appropriate for a particular radiation field. The radiation weighting factors for neutrons to be used are those given in ICRP Publication 103 and given in Table 8-2 and Fig. 8-1. The results of Ref. 2 listed in the appendix to this chapter provide examples of typical neutron energy spectra generated by the accelerators at Fermilab. While shielding calculations pertinent to actual conditions are preferred, such examples may be used to quantify radiation weighting factors used to support shielding assessments.

3. Temporary conditions involving facilities under construction including associated parking lots should be evaluated and criteria of this manual applied where practicable. Deviations from these criteria for such transient conditions shall be approved by the SRSO.

4. Locating parking lots, eating areas, office space, rest rooms, drinking fountains, showers and similar facilities and devices within radiological areas as defined by this Manual and 10 CFR Part 835 is strongly discouraged. Unless office space is essential to support radiological work, steps should be taken to preclude unnecessary occupancy in such areas.

5. As is reasonably possible, shielding assessment calculations and shielding integrity should be verified by comprehensive measurements of the radiation fields as soon as practicable after commencement of operations. Such verifications shall be documented and retained, preferably in ESH&Q docdb or an equivalent electronic document retrieval system, along with the shielding assessment documentation.

6. The Appendix to this chapter gives a summary and short bibliography on the design of accelerator radiation shielding.

Table 8-1 Radiation Weighting Factors for Various Particles

Radiation Type	Radiation Weighting
Photons	1
Electrons and muons	1
Protons and charged pions	2
Alpha particles, fission fragments, heavy ions	20
Neutrons	A continuous function of neutron energy, see See Table 8-2 and Figure 8-1.

Table 8-2 Neutron Radiation Weighting or Quality Factors According to ICRP Publication 103

E_n (MeV)	w_R	E_n (MeV)	w_R	E_n (MeV)	w_R
1.0×10^{-9}	2.50	0.20	14.3	30	6.04
1.0×10^{-8}	2.50	0.30	16.8	40	5.69
2.5×10^{-8}	2.50	0.50	19.3	50	5.50
1.0×10^{-7}	2.50	0.70	20.3	60	5.36
2.0×10^{-7}	2.50	0.90	20.7	75	5.16
5.0×10^{-7}	2.50	1.0	20.7	100	4.86
1.0×10^{-6}	2.50	1.2	20.0	130	4.57
2.0×10^{-6}	2.50	1.5	18.9	150	4.40
5.0×10^{-6}	2.50	2.0	17.3	180	4.20
1.0×10^{-5}	2.50	2.5	16.0	200	4.08
2.0×10^{-5}	2.50	3.0	15.0	300	3.66
5.0×10^{-5}	2.50	4.0	13.3	400	3.40
1.0×10^{-4}	2.50	5.0	12.0	500	3.23
2.0×10^{-4}	2.50	6.0	11.1	700	3.01
5.0×10^{-4}	2.50	7.0	10.3	1.0×10^{3}	2.84
1.0×10^{-3}	2.51	8.0	9.72	1.5×10^{3}	2.70
2.0×10^{-3}	2.53	9.0	9.22	2.0×10^{3}	2.63
5.0×10^{-3}	2.67	10	8.81	3.0×10^{3}	2.57
1.0×10^{-2}	3.03	12	8.16	5.0×10^{3}	2.53
2.0×10^{-2}	3.92	14	7.67	1.0×10^{4}	2.51
3.0×10^{-2}	4.84	15	7.47	2.0×10^{4}	2.50
5.0×10^{-2}	6.58	16	7.30	5.0×10^{4}	2.50
7.0×10^{-2}	8.10	17	7.14	1.0×10^{5}	2.50
0.10	10.0	18	7.00	1.0×10^{6}	2.50
0.15	12.5	20	6.76	1.0×10^{7}	2.50

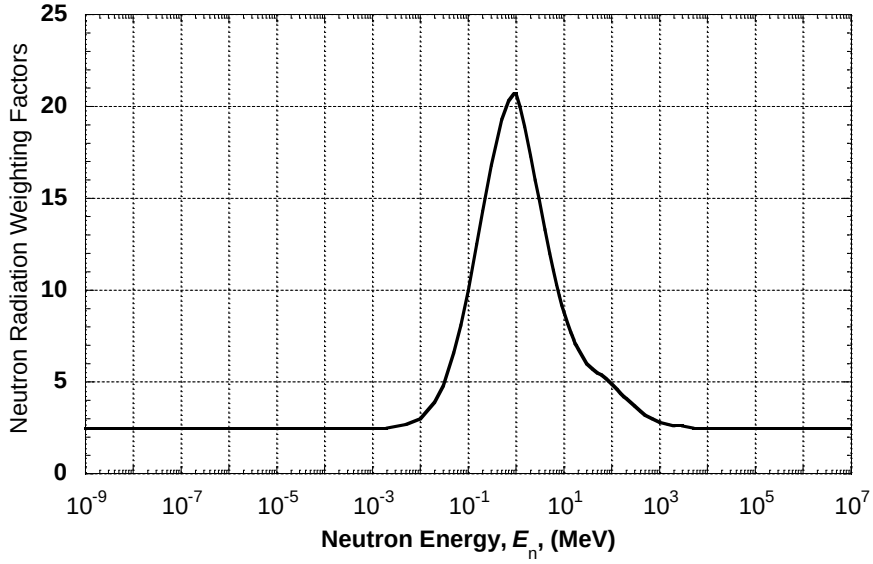

Figure 8-1 Neutron Radiation Weighting (Quality) Factors as a function of neutron energy. (Based on ICRP Publication 103.)

813 Responsibilities for Configuration Control of Radiation Shielding

Division/Section Heads, with the support of the assigned RSOs, are responsible for management of radiation shielding pertaining to the accelerators, beamlines and associated experiments designed, constructed, and operated by them as assigned by the Fermilab Director. Coordination between different organizations is common, required, and naturally expected. The Head of the Facilities Engineering Services Section (FESS) has special responsibilities pertaining to accelerator/beamline/experiment radiation shielding specifically attributed to that organization in the list below that require coordination with the responsible Division/Section(s). The Fermilab Shielding Assessment Review Panel (SARP), the Chair of which is a member of the Radiation Safety Subcommittee of FESHCom has key roles in the reviews of shielding assessments as specified elsewhere in this Chapter.

The responsibilities of the Division/Section(s), where necessary coordinated with FESS, include these program elements:

1. Develop and maintain a comprehensive inventory of accelerator/beamline/experiment shielding against ionizing radiation in the areas assigned to them by the Director, and assure that the shielding complies with provisions of this manual. The inventory most likely will take the form of a set of civil construction drawings overlaid with beamline components maintained in an accessible electronic format. Portable or movable shielding and devices installed either temporarily or permanently within larger, permanent facilities that are

required to achieve a given level of radiation protection shall be documented, perhaps on overlays to civil construction drawings.

2. Conduct appropriate shielding assessments when new accelerators, beamlines, or experiments are designed as specified further in subsequent Articles in this chapter.

3. Revised shielding assessments shall also be conducted when accelerator/beamline/experiment operating conditions change significantly, including those that affect the approved Accelerator Safety Envelope (see FESHM 2010) or result in a change to the posting levels (see Article 236) applicable to a given areas..

4. Assure review and approval of shielding assessments in accordance with the process described in Article 814.

5. Maintain documentation of the shielding of beamlines in their area of responsibility. Determine and document appropriate beam operating parameter limits required to meet ES&H requirements specified both in the FRCM and in FESHM 2010. This includes the Accelerator Safety Envelope (ASE) elements that are connected with radiological shielding.

6. Prepare shielding assessment addenda to reflect minor changes to a given area covered by a previously approved shielding assessment, Such changes include those that do not affect the approved Accelerator Safety Envelope (see FESHM 2010), do not significantly change operating conditions such as the available intensity, energy, or particle type, etc., or do not reduce the level of safety as defined by the various posting levels of Article 236. At the discretion of the responsible Division/Section, these addenda, commonly called “post assessment documents” may be approved internally or sent to the SARP for further review. They are to be permanently documented along with the approved Shielding Assessment in a permanently maintained document retrieval system.

7. The placement of temporary shielding in accelerator/beamline enclosures should be controlled by some or all of the following provisions:

    a. Provide appropriate labeling and securing of such shielding to prevent its inadvertent removal,

    b. Develop appropriate procedures for evaluating its effectiveness, and integrity,

    c. Develop and retain appropriate documentation inventory, which becomes part of the permanent record of the operation.

8. Responsibilities for required as-built shielding documents and drawings are as follows:

   a. FESS shall prepare and maintain the original set of "as-built" drawings documenting the status of radiation shielding for civil structures.

   b. Divisions/Sections shall augment such drawings to encompass required portable shielding or devices and provide this documentation to FESS.

   c. The drawings shall be approved by the responsible Division/Section safety personnel at 3 stages; conceptual design (meaning development of specifications), prior to bidding, and as-built. These approvals are congruent with the shielding assessment process discussed in Article 814.

   d. Thereafter FESS will maintain the up-to-date originals of the civil drawings (and retain archival drawings of past conditions) while the ESH&Q Section and the appropriate Division/Section/ will be supplied up-to-date copies of the current shielding conditions.

814 Shielding Assessment Preparation, Review, and Approval Process

The flowchart shown in Fig. 8-2 illustrates the shielding assessment, review, and approval process. It applies to upgrades as well as new designs.

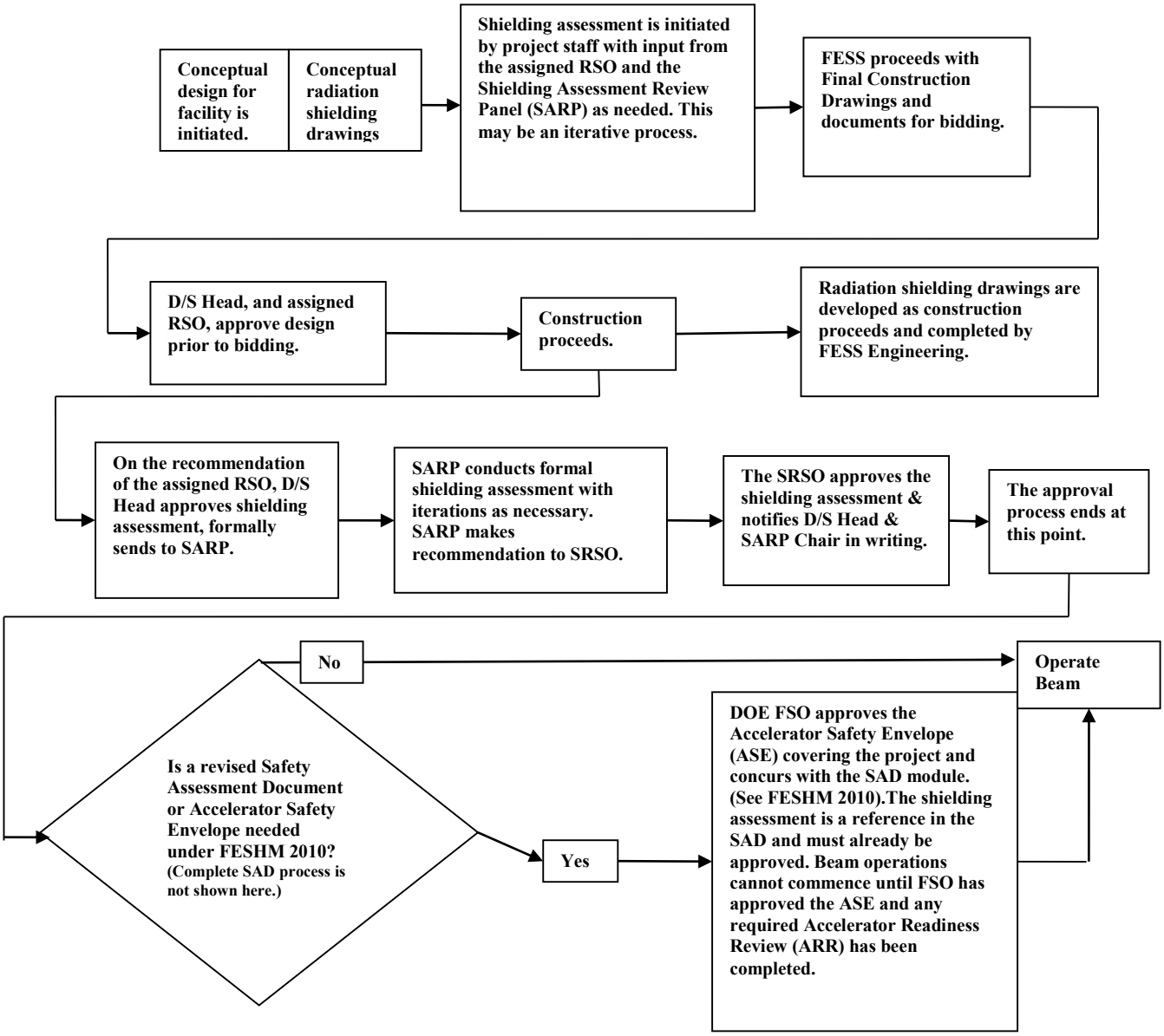

Fig. 8-2 Fermilab Radiation Shielding Design Review Process

1. Division/Section ES&H personnel shall be intimately involved in all stages of the process, from the conceptual stage through operations. All final designs, including

construction packages ready for bid must be reviewed and approved by Division/Section management and by the assigned RSOs

2. A preliminary shielding assessment should be conducted and documented at the design specification stage of conceptual development and include project staff, the originating assigned RSOs, and those responsible for designing the facility. Where civil construction is needed, representatives of FESS shall be included. This specification stage should identify the desired personnel occupancy state for the final design.

3. New or modified shielding configurations, including required moveable or portable shielding shall be reviewed by FESS for structural engineering impact.

4. The shielding assessment, at least at a preliminary level, shall be approved by the assigned RSO prior to the project being released for bid. Such a preliminary approval shall be clearly labeled as such and the criteria for final approval clearly documented. For complex installations, the process should be iterative, with the SARP consulted at the earliest practicable stage.

5. The final assessment shall be reviewed internally within the originating Division/Section(s) and approved in writing by the responsible Division/Section Head(s).

6. After approval of the final shielding assessment by the originating Division/Section (s), the assessment shall be formally transmitted to the SARP for review in a timely manner prior to the planned conduct of the operations covered in the assessment.

7. SARP shall review the shielding assessment in accordance with its charter embodied in the charter of the Radiation Safety Subcommittee. There may be iterations in this process with the affected Division/Section(s) as designs develop.

8. Upon successful completion of its review the SARP shall transmit its recommendation for approval to the Senior Radiation Safety Officer (SRSO).

9. The SRSO shall:

    a. Review the report of SARP and the shielding assessment and approve of the shielding assessment if it is appropriate.

    b. Notify SARP and the originating Division/Section Head(s) in writing of this approval or of reason for disapproval.

c. Maintain records of such reviews including file copies of the "as-built" shielding documents including drawings and the shielding assessment documentation and review protocols.

10. All approvals of these documents may be done in electronic format. The electronic approvals shall clearly indicate the version being approved by document number, date, etc.

11. FESS Engineering shall be provided copies of all final approval documents to the ESH&Q Section and the appropriate Division/Section for inclusion in its site-specific shielding file.

815 Content of Shielding Assessments

1. New or modified accelerator/beamline facilities shall have a shielding assessment performed, as specified in Article 813. Many reference documents have been generated over the years at Fermilab and elsewhere that describe accelerator shielding design and radioactivation. Some of these can be found at: http://esh.fnal.gov/xms/Resources/Shielding-Assessments. These may be incorporated by reference in the accelerator/beamline shielding assessments.

2. The shielding assessment shall be a written description that includes calculations and measurements of possible radiation exposures, radiation shielding, beam optics and other relevant information. It shall address soil and groundwater contamination, airborne radionuclide releases and any associated required monitoring activities. It may incorporate the analysis of non-radiological effects connected with the assessment of ionizing radiation hazards. A prominent example is structural analysis of heat-loading driven by energy deposition of energetic particles also connected with prompt radiation dose rates and/or residual radioactivity production.

3. The Accelerator Division has developed and maintains an established protocol for conducting such shielding assessments. This document is denoted ADSP-02-0110. This should serve as a reference for shielding assessments.

4. Results of shielding assessments conducted using methodologies established prior to the amendments to 10 CFR 835 issued in June 2007 remain valid in view of the analysis of Ref. (2 in the Appendix to this chapter. Shielding assessments conducted after January 1, 2010 shall employ updated methodologies based upon ICRP Publication 103 (see Article 812).

5. A modification to shielding which requires a new or revised shielding assessment under Article 813 is one that:

a. results in a significant change to operating conditions,

b. affects the approved Accelerator Safety Envelope, or

c. Permanently changes the level of personnel protection as defined in Article 236.

Changes to shielding that do not require a new or revised shielding assessment under these criteria may be documented in a shielding assessment addendum, also called a "post assessment document", and formally approved internally within the responsible Division/Section by the assigned RSO(s) and the Division/Section Head.

6. The shielding assessment must document the circumstances and controls that serve to limit the intensity of the maximum beam loss and/or its duration and the resulting dose. This specifically includes a description of required portable or movable shielding and beamline components.

7. The final assessment shall establish the occupancy status and radiological posting requirements of areas with respect to the posting criteria of Articles 234 and 236.

8. Completed shielding assessments and their approvals are generally based upon design and construction drawings, inclusive of field modifications, and other related documents as they are developed during the construction process.

APPENDIX - Brief Synopsis of Methodologies for Assessing the Shielding of Particle Accelerators

At high energy particle accelerators the design of adequate shielding becomes complex with increasing beam energy due to cascade phenomena. A high-energy hadron interacting with a nucleus typically creates a rather large number of short-lived particles (pions, kaons, etc.), as well as protons, neutrons and nuclear fragments. Another important result of high-energy hadron interactions is the production of muons, which can represent a significant shielding problem. The interactions of the high energy beams can also produce significant radioactivation of the beamline components, the prompt radiation shield, and the surrounding environment. Even hadrons of relatively low energies can produce significant radiation fields and the possibility of radioactivation of materials including environmental media.

Likewise, electrons of all energies can produce significant prompt radiation fields. At the lowest energies these radiation fields are dominated by photons. Above kinetic energies of a few MeV neutrons can be produced by electron interactions with matter while above 211 MeV muon radiation fields are possible. In the environs of electron radiation fields, residual radioactivity can be produced. Thus the shielding of radiation fields associated with electron beams and even muon beams can also be important at Fermilab, especially as the program of the Laboratory continues to be developed and future facilities designed, constructed, and operated.

Shielding design at Fermilab shall be performed in a high quality manner. A great deal of expertise on this topic is available in the ESH&Q Section, the Accelerator Division and the SARP as well as individuals located elsewhere within the Laboratory. A large body of documentation is available on these issues in publications, Fermilab reports (TMs, FNs, Confs, and Pubs.) and in published literature in accelerator science and health physics.

Many practical problems are amenable to phenomenological approaches of longstanding use at Fermilab and elsewhere. Some of these approaches are clearly of benefit in job planning activities, etc. However, for new designs in most circumstances it is far better to perform calculations specific to the details of the shielding configuration encountered than it is to excessively employ generalized calculations and “rules of thumb”. Thus, when practicable, modern shielding codes such as MARS should be used in accordance with FESHM Chapter 2090, "Usage of Computer Calculations Affecting Environment, Safety, and Health." Proper use of shielding computer models at the design stage can prevent design errors that are typically costly and difficult to correct.

The properties of shielding materials, especially their elemental composition and density is of high importance in the design of radiation shielding and should be carefully considered in the conduct of shielding calculations. For example, some backfill materials

that are similar to concrete or soil in elemental composition may be of lower density than the "standard" values.

There is a large number of technical references that address the topics of this chapter. Two key ones are cited below and these contain numerous references to other related publications:

1. Fermilab TM-1834, "Radiation Physics for Personnel and Environmental Protection" by J. D. Cossairt, posted on the following website: https://esh-docdb.fnal.gov:440/cgi-bin/ShowDocument?docid=1007.

2. Cossairt and Vaziri, "Neutron Dose per Fluence and Weighting Factors for Use at High Energy Accelerators", Health Physics 96 (2009)617-628.